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TECHNICAL BRIEF

SOUND PROPAGATION AND ATTENUATION CHARACTERISTICS OVER A HEAVILY VEGETATED TERRAIN

WYLE LABORATORIES
TESTING DIVISION, HUNTSVILLE FACILITY

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SOUND PROPAGATION AND ATTENUATION CHARACTERISTICS OVER A HEAVILY VEGETATED TERRAIN

for

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1.0 INTRODUCTION

This program is an effort to establish a rational basis for developing practical engineering methods for predicting sound propagation losses over areas covered with thick vegetation or forest. In dealing with problems in this regime, the concept of layered media boundary condition is of prime importance. This study is being conducted through both analytical and experimental approaches.

The analytical study comprises two cases. In the first case the ground cover has a significant thickness such that a layer description is warranted. Physically, a dense vegetation of more than several inches depth should definitely be considered as a layer. In this case only wave propagations above the ground cover is considered. In the second case, the ground cover has a depth large in comparison to the source or receiver height. Hence, in addition to ground attenuation effects due to reflection, wave transmission inside the ground cover should also be examined.

The experimental studies have been designed to be performed in laboratory conditions to facilitate readily controllable environments and simple experimental procedures for verifying the theoretical predictions. It is also intended to use this laboratory experimental program as a guide to future field measurements. These studies consist of three parts. In the first part, the acoustic parameters for four types of simulated ground cover materials will be measured. The parameters include flow resistance, porosity, propagation constants, and normal impedance. The second part is propagation loss measurements in laboratory scale. Two key geometrical parameters, i.e., the range distance to ground cover depth ratio and the wave length to ground cover depth ratio, will be used to control the test program. A wide range of these parameters can be arranged for the laboratory scale test. Finally, the third part consists of measurements of actual soil sample acoustic properties.

The purpose of this interim report is intended for an outline of the up-to-date progress on this project. The essential portion of the theoretical analysis and a significant amount of parameter studies have been completed. The design and setup of experiments are also complete, and the measurements of ground cover effects are currently underway. In the sections that follow, Section 2.0 is an outline of the mathematical formulations; Section 3.0 presents some results and discussions of the computer parameter studies; and Section 4.0 summarizes the important aspects of the experiments.

2.0 MATHEMATICAL FORMULATIONS

A spherical wave front which is originated from a point source can be represented as an integral of its plane wave elements

$$\frac{e^{ikr}}{kr} = \left(\frac{i}{2\pi}\right)\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}+i\infty} e^{i(k_1x + k_2y + k_3(h-z))} \sin\theta d\theta \qquad (1)$$

This representation was first given by Weyl (Reference 1) in 1919. In the above integral, the vector (k_1, k_2, k_3) identifies the wave number of a plane wave element. The path of integration over θ is extended to infinity mainly to account for the singularity of the wave function at the point source itself. The reflection of the primary wave at a boundary can evidently be represented as

$$p_r = \left(\frac{i}{2\pi}\right)\int_0^{2\pi} d\phi \int_0^{\frac{\pi}{2}+i\infty} e^{i(k_1x + k_2 + k_3(h+z))} R(\phi,\theta) \sin\theta d\theta \qquad (2)$$

where $R(\phi, \theta)$ is the plane wave reflection coefficient. The reflection coefficient $R(\phi, \theta)$ is a function of ϕ and θ.

It is more convenient for the purpose of integration to write Equation (2) in another coordinate system. In the new coordinate system, (Figure 1) the principal direction of reflected ray path is chosen as an axis. The new angular variables are defined as ψ and η. Equation (2) can now be represented as

$$p_r = \left(\frac{i}{2\pi}\right)\int_0^{2\pi} d\psi \int_0^{\frac{\pi}{2}+i\infty} e^{ikr_2\cos\eta} R(\psi,\eta) \sin\eta\, d\eta \qquad (3)$$

An integral of this form can be evaluated by using the method of steepest descent, (Reference 2). In the acoustic far field, the value of kr_2 is very large compared to unity. On most of the paths of integration in the complex η-plane, the value of the exponential function oscillates rapidly and therefore it is not feasible to integrate Equation (3) either analytically or numerically. However, a path (or paths) does exist such that the phase of the exponential function remains constant while its magnitude decreases rapidly along this path (Figure 2). The point at which the modulus of the exponential function reaches a maximum is the so called saddle point in the complex η-plane for the function $\cos\eta$. Along the paths of steepest descent, a new variable can be defined such that

$$\cos \eta = 1 + i t \tag{4}$$

where t is real and positive.

The reflected wave can then be written as

$$p_r = \frac{e^{ikr_2}}{kr_2} (kr_2) \iint_0^\infty e^{-kr_2 t} R(\psi, t)\, dt\, d\psi = \frac{e^{ikr_2}}{kr_2} Q \tag{5}$$

which has the form of a wave originating from an "image source" with the strength Q.

For an arbitrary given function of $R(\psi, \theta)$, Equation (5) can only be integrated approximately. A first asymptotic approximation has been given by Brekhovskikh (Reference 3) as

$$p_r = \frac{e^{ikr_2}}{kr_2} \left\{ R(\gamma_0) + \frac{1}{ikr_2} \left(\frac{1}{2} (1 - \gamma_0^2) R''(\gamma_0) - \gamma_0 R'(\gamma_0) \right) \right\}$$

where

$$\gamma_0 = \cos \theta_0 \tag{6}$$

and the derivatives of R are differentiations with respect to $\gamma = \cos \theta$. For some special forms of reflection coefficients, a complete asymptotic expansion or even a closed form representation for the reflected wave can be obtained, (References 4 and 5).

Equation (6) serves as a starting point of the present layered media ground attenuation theoretical investigation.

Figure 3 illustrates some geometrical features of wave reflections from a single layer ground cover of finite thickness. A part of the incident primary wave is reflected directly at the top of the ground cover. Part of the incident wave penetrates into the ground cover layer. As this refracted wave reaches the ground surface itself, it is again reflected and part of it re-emerge as a second reflected wave. When the combination of these two reflected waves is regarded as a single reflection, a composite reflection coefficient can be assigned to the layered ground cover media.

In the present study, the ground cover layer is considered to be a wave bearing medium. The ground surface is assumed to possess a normal impedence which is independent of the angle of incidence. Therefore, the composite reflection coefficient can be written as

$$R = R_1 + R^* \tag{7}$$

where

$$R_1 = \frac{\cos\theta - \beta_1 \cos\theta_1}{\cos\theta + \beta_1 \cos\theta_1}$$

$$R^* = T_{12}\, T_{21}\, R_2\, \Phi$$

$T_{12}T_{21}$ = Transmission Coefficients $= \dfrac{4\beta_1 \cos\theta \cos\theta_1}{(\cos\theta + \beta_1 \cos\theta_1)^2}$

R_2 = Reflection Coefficient $= \dfrac{\cos\theta_1 - \beta_2}{\cos\theta_1 + \beta_2}$

Φ = Phase Shift $= \exp\left\{2h\,(n^2 - 1 + \cos^2\theta)^{1/2}\right\}$

n = Refraction Coefficient

β_1, β_2 = Specific Admittance Ratios

A computing program has been compiled to perform an extensive parameter study for the characteristics of the ground attenuation effects for wave propagation over a layered media. All the parameters can be assigned independently. The ground effect attenuation pattern is computed for all points in a 20 x 20 rectangular grid where the dimension of the grid is adjustable. The results can also be plotted directly as sound pressure level contour curves on a digital x-y plotter.

3.0 RESULTS AND DISCUSSIONS OF THE PARAMETER STUDY

In the computations of ground attenuation parameter studies, all the length scales are normalized with respect to the wave length of the primary wave in the air. The independent parameters are

- Impedence of the ground cover material
- Impedence of the ground surface
- The refraction coefficient of the ground cover medium with respect to air
- Height of the sound source above the top of the ground cover
- Thickness of the ground cover layer

The first three parameters are, in general, complex numbers.

The computer parameter studies have so far covered only a limited range of parameters. A large number of cases have been concentrated on parameter combinations relevant to actual field conditions. The impedence ratio and refraction coefficient of the ground cover are generally compatible with what one would expect from a low density porous medium. The impedence of the ground surface is assumed to be large. The discussions below are mainly intended for calculations in this group. Several important points are presented as

a) The computating scheme is very accurate for ground attenuation predictions in the far field, say, $kr > 10$. Some numerical results given by Ingard (Reference 4) have been regenerated and found to be in close agreement with the original Ingard computations. Equation (6) is, indeed, the first approximation to the more accurate analytical result for the case of a normal impedence boundary condition. One of the computed cases is shown in Figure 4.

b) The significance of the layered media concept has been clearly born out by this parameter study. When both the sound source is on top of the ground cover, the attenuation level immediately above the ground cover is independent of the layer thickness. However, the wave intensity directivity pattern above the ground vs a marked dependence on the layer thickness. For a case where

$$\beta_1 = 1.20$$
$$\beta_2 = 0.50$$
$$n = 1.50$$

The attenuation directivity pattern for a ground cover of 1/4 wavelength thickness has a much smaller SPL gradient in the vertical

direction that the corresponding directivity pattern for a ground cover of 1/2 wavelength thickness (Figure 5). The average sound attenuation near the ground is 5 dB higher for the 1/4 wavelength ground cover thickness.

c) When the sound source is above the ground cover for more than one wavelength, the ground level attenuation shows significant dependence on the layer thickness. For the same impedences and refraction coefficient as given in (b), the attenuation for the 1/4 wavelength layer is about 5.7 dB about that for the 1/2 wavelength layer. This is true for source heights ranging from one to five wavelengths above the ground cover. A case where $s = 3\lambda$, or $ks = 18.84$, is given in Figure 6.

d) The ground cover material studied in (b) and (c) is similar to a porous medium in which is speed of sound is closed to the isothermal speed of sound in the air. The structure of the layer offers a moderate refraction effect. Such a layer with a thickness of 8" can produce 6 dB more of excessive attenuation in the frequency band near 400 Hz.

It should be emphasized again that the above conclusions apply to only a narrow range of cases. Nonetheless, it clearly indicates that the layer effect is theoretically realistic and can indeed be very important.

e) In the above mentioned cases, the ground layer is non-dissipative. For a dissipative layer, the ground attenuation pattern approaches rapidly that of a semi-infinite ground cover as the dissipation coefficient increases.

4.0 IMPORTANT ASPECTS OF THE EXPERIMENTAL PROGRAM

The design and procedures of the laboratory scaled ground attenuation measurements have been carefully reviewed during the past months. The preparation and setup of the experiments have also been completed. Measurements are currently underway. Several important aspects of the experimental program are discussed here as follows:

<u>The Test Platform and the Simulated Ground Cover Materials</u>

The dimensions of the test platform are 20 feet by 8 feet. The construction of the plywood platform, the setups of sound source, microphones and associated electronic equipment have been relative straightforward. However, the choice of ground cover material for this particular test becomes a new experience. It is found from past experiences here at Wyle Laboratories that wave propagating at glancing incidences can penetrate through a cover layer over the boundary only if the density of the cover material is very low. Ordinary types of acoustic materials may behave like a semi-infinite layer in this occasion. On the otherhand, the layer material has also to be uniform and structurally stable for the purposes of this experiment. Two outstanding candidates have been chosen, and a third one has been chosen as a secondary testing material.

- Rubberized Horsehair – This material has an elastic interlocking matrix with large openings between fibres. It is commercially available in 2" thickness. It is originally used for package purposes. This material will be used for simulated ground cover of two and four inch thicknesses.

- Fiberglas Air Filter – Despite of its extremely low density, this material has an excellent structural and dimensional stability. It is also uniform. This material is available in one inch thickness. It will be used for simulated ground cover of two and four inch thickness.

- Fiberglas Batts – This material is relative dense in comparison to the above two materials. However, some information is available in the literature regarding its acoustic properties. A four inch batt will be used in this experiment.

For each material at each thickness, four sound source height will be arranged for the measurements. For each sound source location, data will be taken at six microphone positions over a frequency range from 500 Hz to 20 K Hz. By doing so, a wide range of normalized parameter ranges can be encompassed. The repeatition of a large number of important cases can further offer better confidence level for the interpretation of results.

Measurements of the Acoustic Parameters of the Testing Material

In this program, the measurements of acoustic properties of the ground cover material is considered to be very important as far as comparison with the analytical results is concerned. An impedence tube for performing precision impedence measurements has been built and calibrated. The detailed design and function of this apparatus have been given by Beranek (References 6, 7, 8). By using this method, the measurement procedures have been significantly economized. A data reduction computing program has also been compiled in connection with the impedence measurements. Some results have been obtained. The same apparatus, with some modifications to the sample holder, will be used to measure the impedence of small soil samples.

In addition to the impedence measurements, the speed of sound in the acoustic material is also an important parameter for ground attenuation estimates. Some measurements will be made in the later portion of this program. Some recent work in this field may serve as useful references (References 9,10).

Comparisons Between Theory and Experiment

It is expected that descrepencies will occur in the prediction/measurement comparisons. Therefore uncertainties in all phases of this program shall be reviewed and compared to results of previous work in the literature. A literature survey will be undertaken in the later part of this program.

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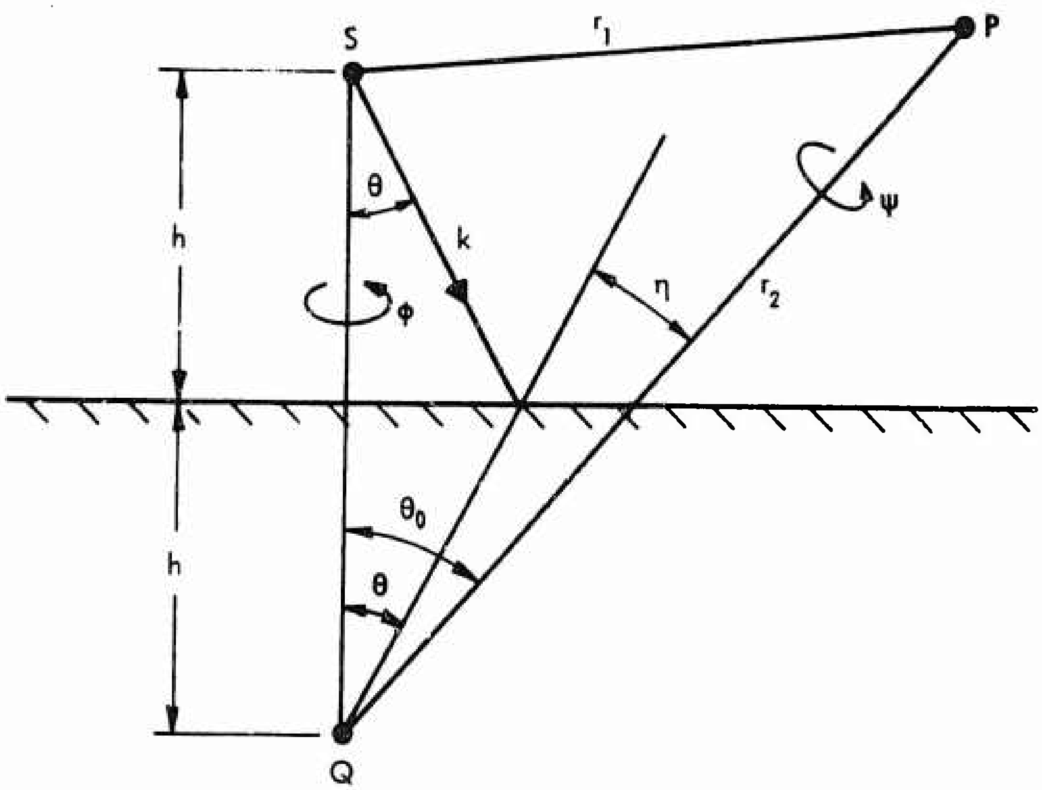

Figure 1.. Coordinate Systems Employed by Ingard in His Theoretical Treatment of Ground Attenuation (Reference 4)

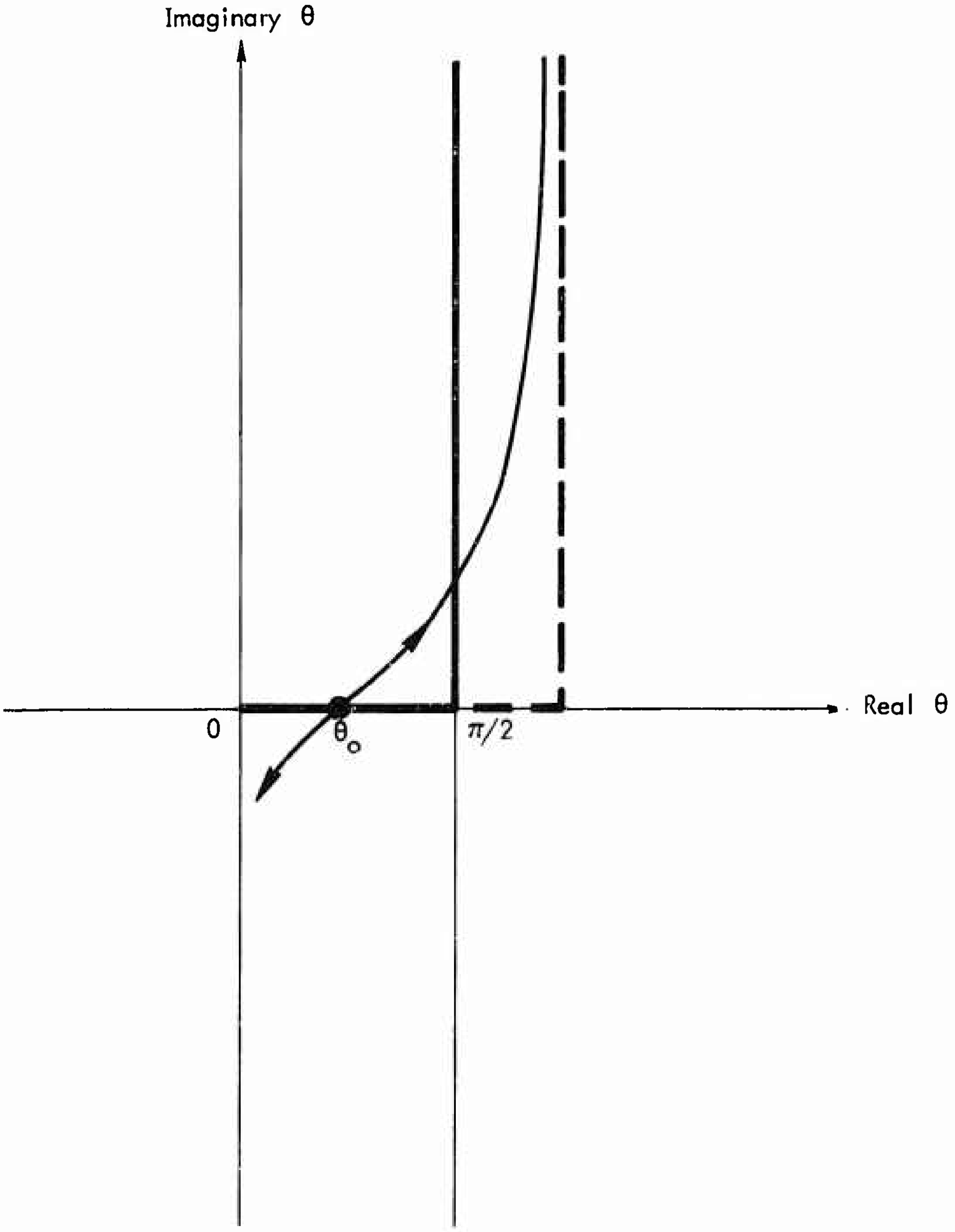

Figure 2. The Paths of Steepest Descent

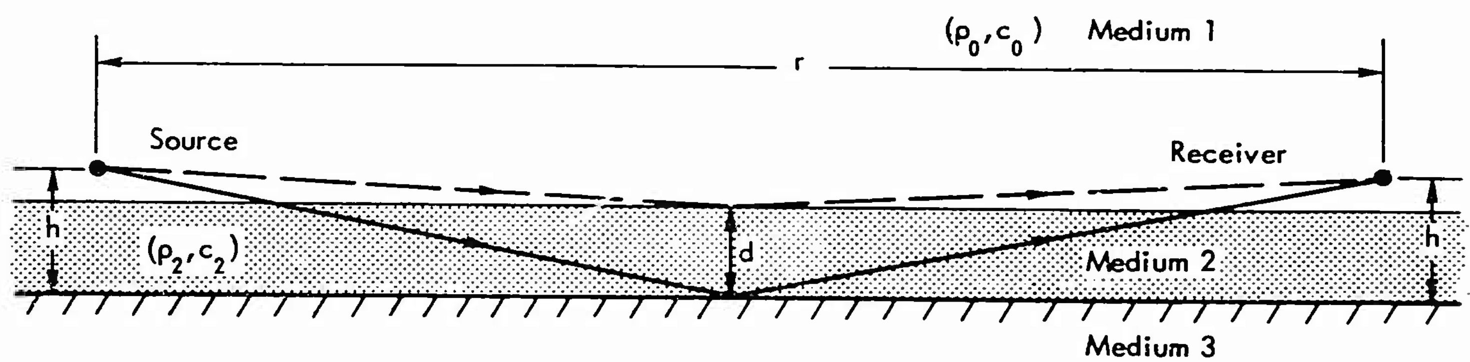

Figure 3. Reflection of Plane Wave From Layered Media at Nearly Grazing Incidence Angles.

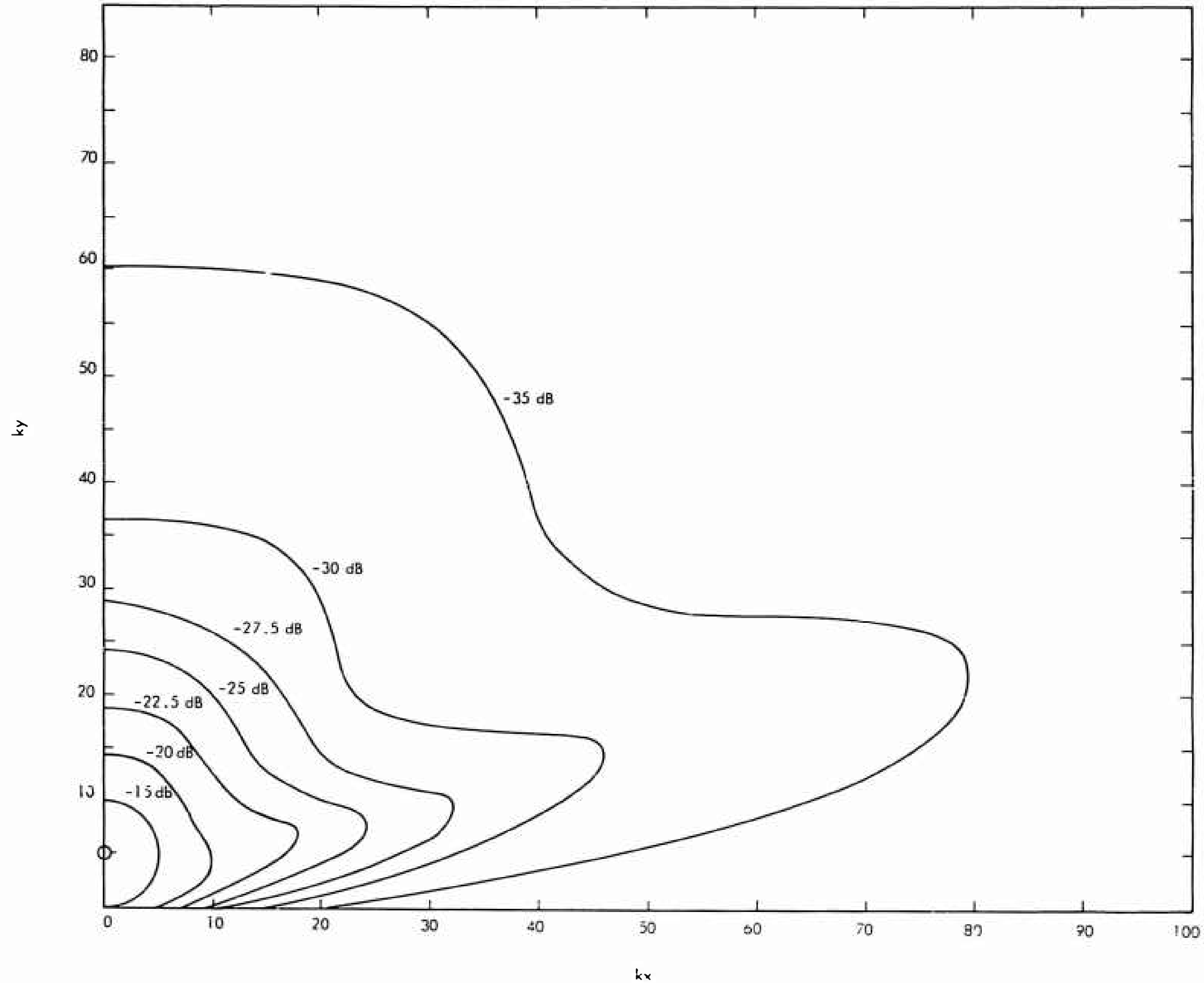

Figure 4. Ground Attenuation Directivity Pattern for a Normal Impedance Boundary with [illegible] 1. The present computation is in close agreement with the results given by Ingard (Reference 4)

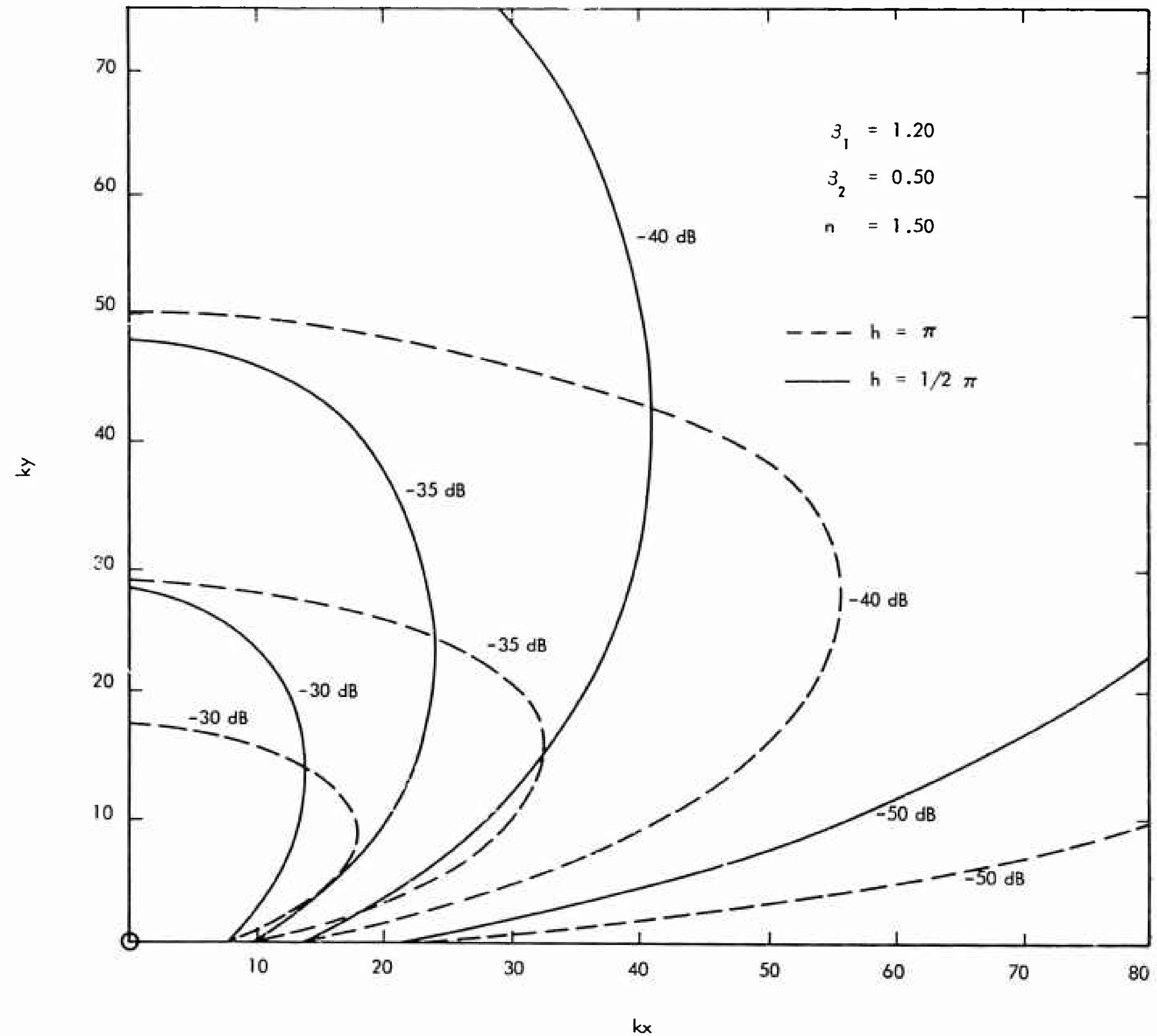

Figure 5. Ground Attenuation Directivity Patterns for Two Different Layer Thicknesses. Source Height Equals to Zero.

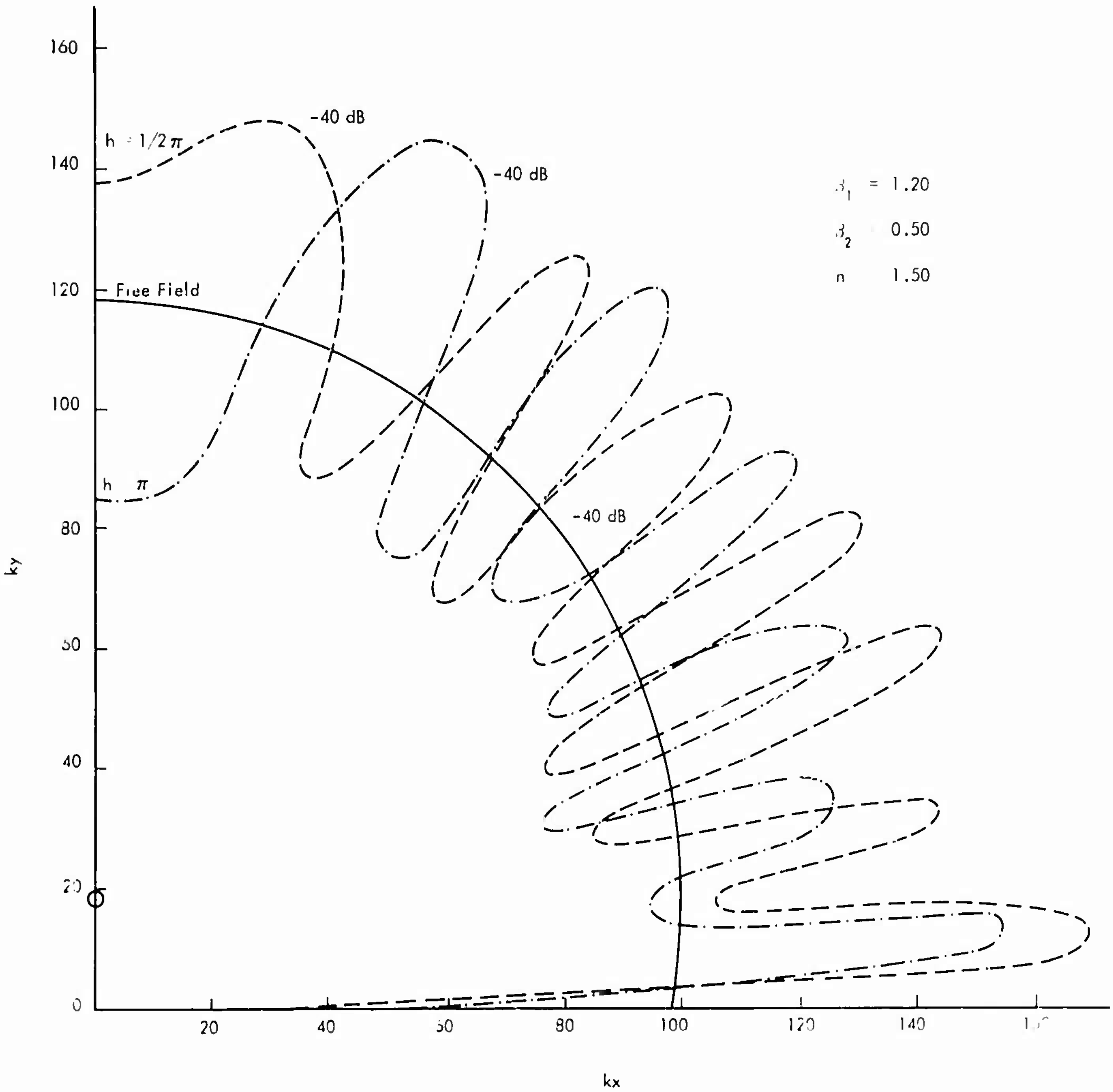

Figure 6. Ground Attenuation Directivity Patterns for Two Different Layer Thicknesses. Source Height Equals Three Wavelengths.

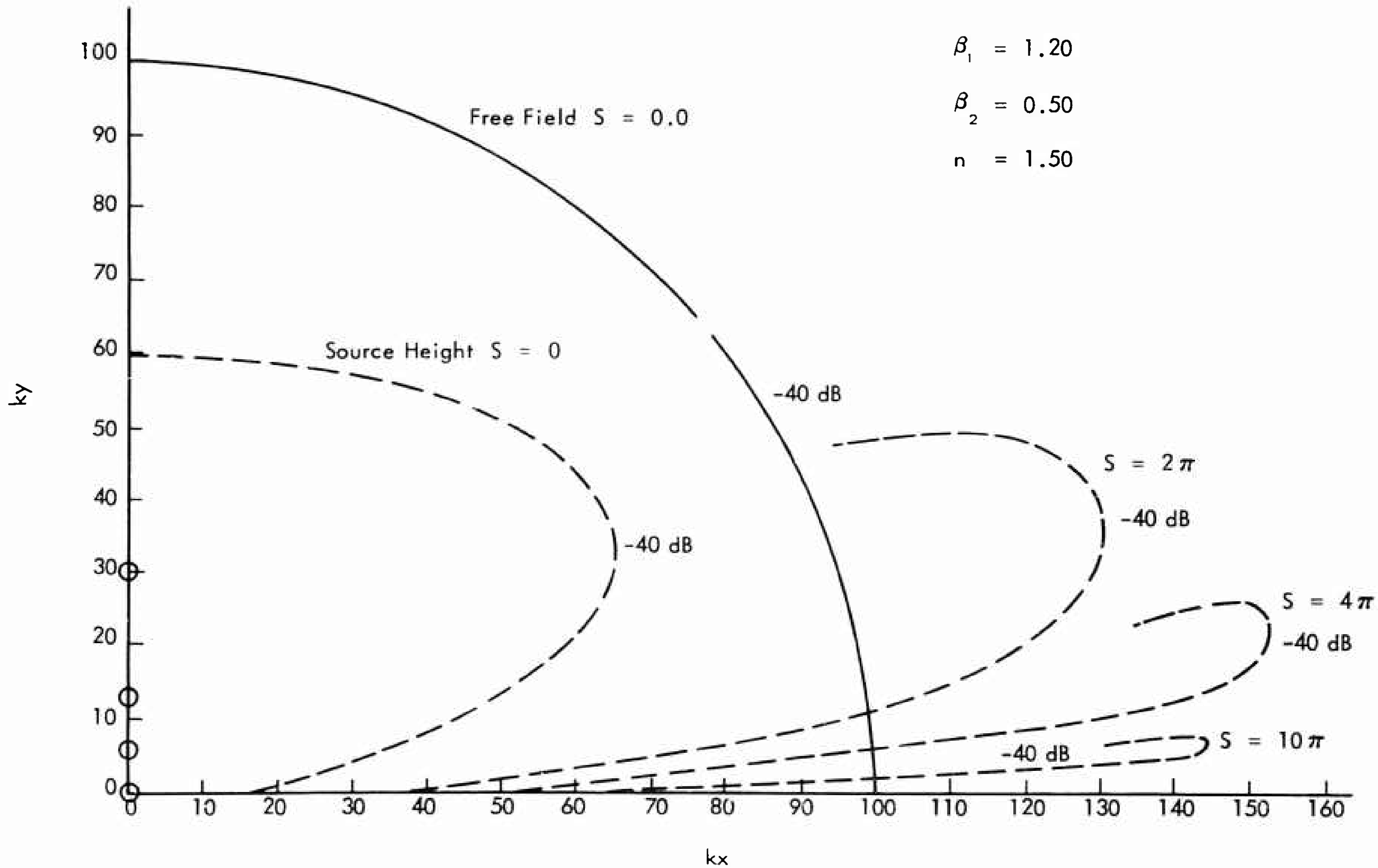

Figure 7. Attenuation Patterns Near the Ground for Various Source Heights

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13. ABSTRACT

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14. KEY WORDS

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